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HARMONIC OPERATION OF SAW ELECTROMAGNETIC TRANSDUCERS,(U)
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For many NDE applications, coverage of an extremely broad range of frequencies is required to characterize a defect or gradient. Non-contact SAW Electromagnetic transducers appear to be restricted to relatively small fractional bandwidths by their structure and low coupling. One solution to this problem is overtone operation of the transducers at their odd harmonics which present models do not predict adequately. This situation motivated the derivation of a new equivalent circuit model based on a description of the dynamic fields surrounding transducer conductiors in which the current distributions are allowed to vary. The new results, while in agreement for fundamental frequency operation with the earlier flat field theory, differ in harmonic prediction. Data favors the new theory. As a design example, we present data (corrected for propagation losses and variations in our electronics) for an unmatched electromagnetic transducer (F - .376 MHz)with a constant insertion loss (within ±2 dB) out ot the seventh odd harmonic as predicted by the new theory.

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HARMONIC OPERATION OF SAW ELECTROMAGNETIC TRANSDUCERS

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ABSTRACT. For many NDE applications, coverage of an extremely broad range of frequencies is required to characterize a defect or gradient. Noncontact SAW electromagnetic transducers appear to be restricted to relatively small fractional bandwidths by their structure and low coupling. One solution to this problem is overtone operation of the transducers at their odd harmonics which present models do not predict adequately. This situation motivated the derivation of a new equivalent circuit model based on a description of the dynamic fields surrounding transducer conductors in which the current distributions are allowed to vary. The new results, while in agreement for fundamental frequency operation with the earlier flat field theory, differ in harmonic prediction. Data favors the new theory. As a design example, we present data (corrected for propagation losses and variations in our electronics) for an unmatched electromagnetic transducer (f_o = .376 MHz) with a constant insertion loss (within ± 2 dB) out to the seventh odd harmonic as predicted by the new theory.

Introduction

Recent advances in NDE methodology employ either a variation in transducer frequency or position to obtain sufficient information to describe a defect quantitatively. Because of limited accessibility to the part to be inspected, measurements over a wide frequency band are preferred. Ideally a transducer capable of a constant output over extremely wide-band is needed. For this application, the advantages of the noncontact coupling of SAW electromagnetic transducers are partially offset by the narrow bandwidths of these transducers. The 3 dB fractional bandwidths are typically $1/N_p$ where N_p is the number of transducer periods. As will be shown, this limitation can be overcome by operating the transducer at odd harmonic frequencies. Present theories do not predict accurately the overtone strength of these transducers.

The purpose of the present paper is to utilize a new theory suitable for harmonic prediction and to present information necessary for the design of a transducer operating over a very wide band of frequencies. This new theory is developed and presented in detail by us in reference 1.

Theory

Previous models[2-8] for SAW electromagnetic transducers (EMTs) have been based on the assumption of a uniform current distribution in each transducer winding or strip. For example, in our previous analysis[6] for the flat conductor EMT, the strip current density K_s(amp/m) was considered constant; K_s = I/S, where I is the current in the strip width. This analysis led to a flat field theory solution which satisfied all the boundary conditions imposed by the transducer geometry above a ground plane. The transducer model based on this theory agreed well with experiment for fundamental frequency operation, but deviated from experiment for harmonic transducer operation. We were motivated to examine the observed differences at the higher frequencies.

By allowing the current to vary along the strip width, we obtained new solutions[1] for the dynamic magnetic fields surrounding an EMT array of conductors above a ground plane. Both the earlier and new solutions satisfy Laplace's equation, but they satisfy different boundary conditions on the tangential $\bar{h}$ field. This difference is a consequence of requiring the surface current to satisfy only the condition $\int_0^{S/2} K_s(x)dx = I/2$ rather than be constant.

Calculations of the dynamic magnetic field component at and parallel to the ground plane, as a function of gap spacing, G, between the EMT and ground plane (of infinite conductivity) are shown in Figure 1 for a strip/spacing ratio, S/b = 0.974. The new theory shows that the current distribution is peaked at the edges of the strip. For larger gaps, the magnetic field loses its "ears" and becomes more sinusoidal in shape similar to results for the flat field theory--for large gaps.

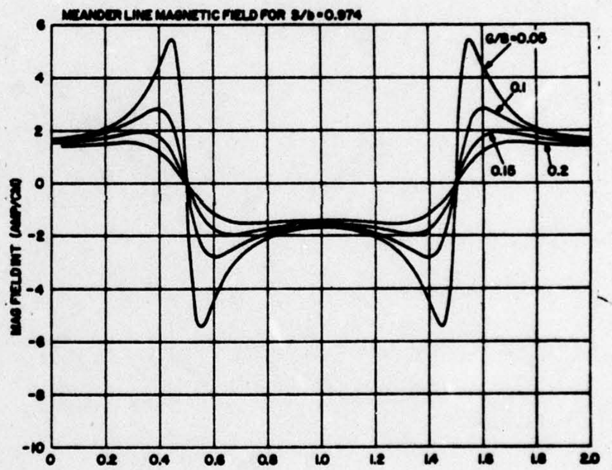

Figure 1. Tangential magnetic field at the ground plane of a meander line for S/b = .974 and G/b = .05, .1 , .15, and .2 for LP theory.

In the new analysis, the solution is expressed in terms of Legendre polynomials and elliptic integrals. There is a direct theoretical correspondence between the EMT surface current distribution and the IDT surface charge distribution on an electrode. In Figure 2 we plot space harmonic amplitudes for both the flat field and Legendre polynomial theories for G = 0. The Legendre polynomial curves for G = 0, can be related to those of Engan[9] for the IDT if S/b replaces 1-a and I/b, V/L in ref 9. In this figure, the differences between the theories for the fundamental are very small and negligible up to S/b ≤ .5. The Legendre polynomial theory departs significantly from the flat field theory for higher harmonics especially as S/b increases (S/b > .2).

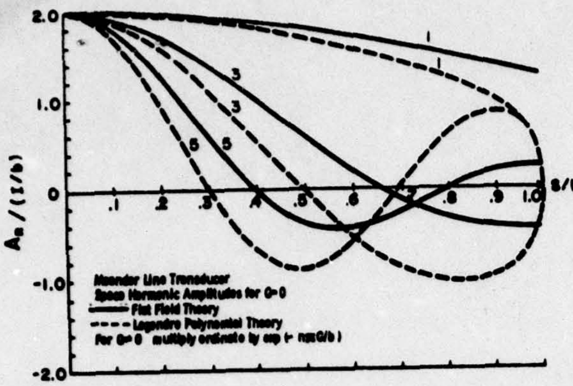

Figure 2. Space harmonic amplitudes for flat field (FF) and Legendre Polynomial (LP) theories.

Equivalent Circuit

A transducer equivalent circuit based on the Legendre polynomial theory for dynamic magnetic fields is shown in Figure 3. The heart of this circuit is the radiation resistance R_A for a uniform transducer:

$$R_A(w) = \left\{ 2w_o l B_o^2 N_p^2 M^2 \right\} (2n+1) \left[\frac{\pi}{4} \frac{Pn(\cos\theta)}{K(\sin(\theta/2))} \right]^2$$

$$\cdot e^{-2(2n+1)\pi G/b} \operatorname{sinc}^2 \left[N_p\left(\frac{w}{w_o} - (2n+1)\right)\right], \qquad (1)$$

in which l is transducer length, $w = 2\pi f$ and w_o is the center angular frequency, B_o (Wb/m^2) is the static magnetic field, M^2 is a material dependent parameter,[5,7] P_n is a Legendre polynomial, K the elliptic integral of the first kind, $\theta = \pi S/b$, 2n+1 is the harmonic number (as in Figure 2) and X_A is acoustic reactance. The electrical parameters include transducer inductance which has two parts: a frequency independent (first order) L_E, and a part L_{EC} dependent on frequency and substrate material conductivity. Resistances include the normal dc value R_E and an eddy current resistance R_{EC}, and R_o, the source impedance. These circuit elements and parameters are explained in more detail in Ref. 1 and 7. The transducer efficiency can be calculated from

$$TE = \frac{2R_A(f)/R_o}{\left| Z_n(f) \right|^2} \qquad (2)$$

where Z_n is a normalized impedance function including the circuit and any matching elements. Insertion loss is defined as IL = -10 log TE.

Transducer Design

If we are to meet our objective of wideband operation, we must examine the critical parameters affecting transducer response over the frequency range of

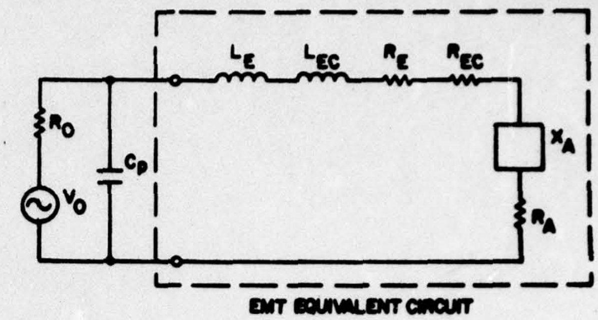

Figure 3. Equivalent Circuit for EMT (Electromagnetic Transducer) with driving source V_o and R_o, and matching capacitor C_p.

interest. In Eq 2 it is the numerator that contains the harmonic information in terms of R_A (Eq 1). The denominator $|Z_n(f)|^2$ is determined by the electrical circuit and matching elements. The acoustic elements R_A and X_A have a negligible influence on $Z_n(f)$; therefore, we can separate out contributions to the overall frequency response of the transducer by evaluating the numerator and denominator of Eq 2 individually.

If we begin with a transducer of a given geometry near a specified metal material at a certain fundamental frequency, we can see from Eq 1 that all these factors are included in the bracketed term. Note that the usual w term has been separated artificially into two factors $w = (w_o)(2n + 1)$. The terms outside the brackets determine the harmonic behavior of the transducer. In fact the parameter of greatest interest is $\theta = \pi S/b$, the strip width to spacing ratio.

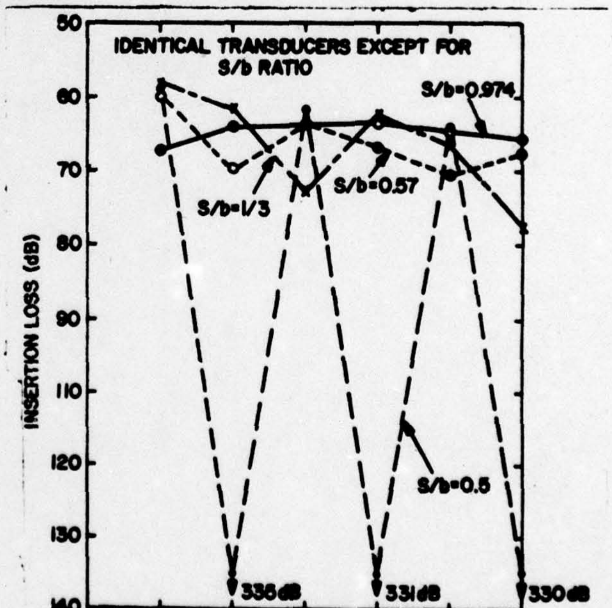

Figure 4. Insertion Loss at harmonic frequencies for S/b = .33, .5, .57, and .974.

In Figure 4 we plot the insertion loss of a transducer and vary S/b as a parameter. The calculated points at the harmonics are connected by straight lines. The $\mathrm{Sinc}^2\left\{N_p\left[\frac{w}{w_o}-(2n+1)\right]\right\}$ function at each harmonic has been omitted for clarity. For the "usual" case when S/b = .5, the theory predicts no third (n = 1) or seventh (n = 3) harmonic. Changing S/b = .57 still results in substantial dips. Going to a smaller ratio, S/b = 1/3, produces a very uneven overall response. A ratio of S/b ≈ 0, not shown in Fig. 4, has a response which is smooth but which varies linearly with frequency, as evident from Fig. 2 and Eq. 1. By choosing an S/b ratio of nearly one (S/b = .974), however, we obtain a fairly constant acoustic response which is flat within ±2 dB out to the eleventh harmonic. This S/b (= .974) ratio is a suitable candidate for harmonic operation.

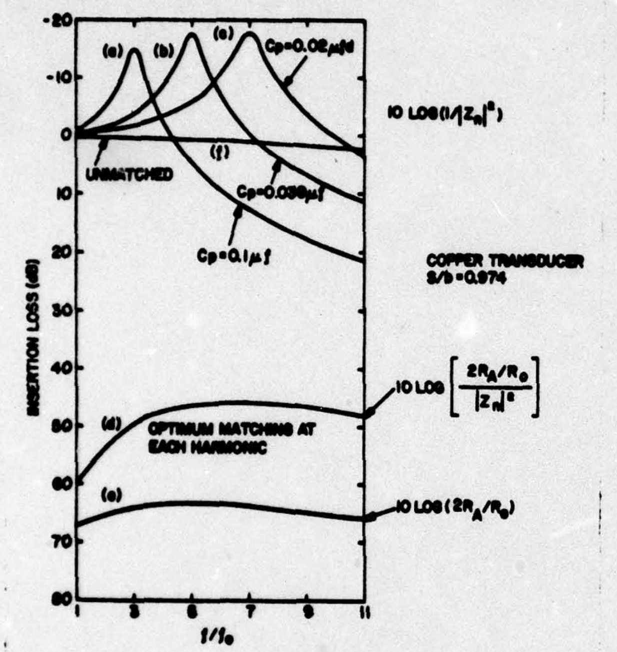

Figure 5. Insertion Loss at harmonic frequencies for various matching conditions.

We must now determine the type of matching to use. To facilitate comparison among different matching conditions, we again omit the detailed frequency response at each harmonic (described by the sinc^2 term in Eq. 1) and plot continuous curves showing the minimum bounds of insertion loss in Fig. 5. At the bottom of Fig. 5 is an insertion loss curve (e) with $TE = 2R_A/R_o$ and $Z_n = 1$ for a transducer having S/b = 0.974. If we match this transducer at each harmonic frequency with a shunt capacitance (a different one at each frequency), then an overall insertion loss variation of 14dB across the band would result as shown by curve (d). Note that curve (d) shows the bounds of the minimum insertion loss obtainable, and it is a smooth curve connecting values calculated at each harmonic frequency. Despite the considerable reduction in insertion loss, the requirement of capacitor replacement at each frequency is not a practical solution. If only one capacitor were used, it would have a sharp peaking effect with a bandwidth equal to the electrical Q as shown by the top three curves of figure 5. The overall response would then be the sum of (a), (b) or (c) with (e).

Note that any one of the capacitor choices would severely raise the insertion loss at adjacent harmonics. Two other possibilities exist: either a more complicated wideband matching scheme or no matching at all. The effect of not matching, as also shown in Figure 5 ((f) + (e)) is a drop of only 2dB across the frequency range. This mild effect is tolerable and unmatched transducers with S/b = .974 were chosen for fabrication.

Experiments

Several transducers were evaluated for their harmonic content. A new technique was used for determining absolute insertion loss of dissimilar transducers in a lossy medium. This method, described in Ref 1., was applied to the evaluation of EMT and piezoelectric transducer combinations on aluminum substates.

In one set of experiments transducers with S/b = .5 were examined. A third harmonic was found, apparently in disagreement with the Legendre polynomial theory. (See Fig. 4) However, on microscopic examination of the transducers, we determined the actual average S/b = .492. Then, recalculation of third harmonic insertion losses brought the LP theory (IL_{LP} = 80dB) in better agreement with experiment (IL_{Exp} = 71dB) than the FF theory (IL_{FF} = 57dB).

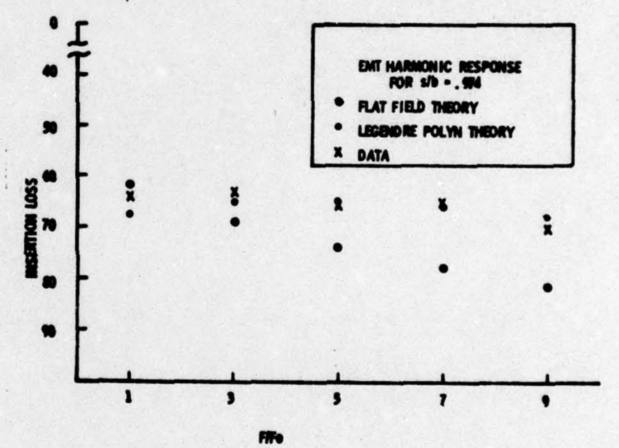

Figure 6. Insertion loss data of an EMT with S/b approximately equal to one compared to the FF and LP theories.

Finally, unmatched transducers with S/b = .974 and f_o = .376MHZ were evaluated and compared with the two theories (see Figure 6). As expected, the transducers had a nearly constant insertion loss. The response was flat to within ± 2 dB out to the 7th harmonic. The 9th harmonic was only down a few dB more. This slight deviation can be attributed to the effects of electrical matching. In addition, the data are clearly in closer agreement with the LP theory.

In conclusion, we have shown that by using the Legendre polynomial theory and by accounting for the effects of electrical matching, it is possible to design an EMT with a flat response (to within a few dB) at odd harmonic frequencies over nearly a decade of range.

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